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Effect of cathodic charging on the crack sensitivity of steel weldments

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EFFECT OF CATHODIC CHARGING ON THE CRACK SENSITIVITY OF STEEL WELDMENTS

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INTRODUCTION

Delayed cracking, a serious problem in steels, is related to the phenomenon by which crack initiation and propagation take place a considerable time after inspection procedures and lead to catastrophic failures. It is observed in materials ranging from rotor forgings, ship assemblies to rocket castings. There are a number of factors such as metal fatigue, temperature effects and aging affects that are believed to be the cause of such failures. Past research has indicated that hydrogen is associated with such failures. Effect of hydrogen is commonly known as hydrogen embrittlement.

Schaeffler, Campbell and Thielsch (1) have defined hydrogen embrittlement as--

> . . . the reduction in the ductility and toughness of steels which is caused by the presence of small quantities of hydrogen.

Most theories indicate that the mechanism of hydrogen embrittlement is diffusion dependent. The important aspects of the mechanism are: 1) precipitation of hydrogen in the molecular form, 2) development of stresses due to external load, and 3) internal defects such as notches, microcracks, etc. The molecular hydrogen formed in areas of microcracks and voids could exert high pressures and cause propagation of cracks

leading to eventual failure. Troiano (7) has shown that hydrogen diffuses to areas of tri-axial stresses and embrittles the steel. Thus in a loaded specimen points of stress concentration are developed to which the hydrogen can diffuse and cause embrittlement.

One of the important areas where hydrogen embrittlement has caused much concern is the delayed cracking leading to failures in steel weldments. Such disastrous effects are most noted in welded structures such as bridges, tanks and ships. Thus delayed cracking of weldments is a service problem. It has been observed that in steel weldments microcracks are formed either in the heat affected zone or in the bead after relatively long periods of time (in the order of months in certain cases) after fabrication.

Hydrogen is introduced into the weld during the welding process. Residual hydrogen could also be present in the base metal itself. Common external sources of hydrogen during welding could be hydrocarbons in the electrode coating, water vapor in air, or grease in the weld area. At high temperatures steel is able to contain greater amounts of hydrogen. It retains almost no hydrogen at room temperature.

Mallet and Rieppel (2) have indicated that combined effects of austenite-martensite transformation and dissolved hydrogen are necessary to cause under bead

cracking in welds.

Beachum (3) has observed that--1) restraint coupled with hydrogen causes delayed cracking, 2) fracture has not been observed in the absence of martensite.

Brown and Baldwin (4) have recorded--

> . . . that high and low temperatures remove embrittlement that hydrogen confers on steel at room temperature.
>
> . . . At high strain rates the metal is ductile.
>
> . . . degassing removes embrittlement.

Past research has indicated that to avoid hydrogen embrittlement the only way is to control and prevent the entry of hydrogen into steel weldments.

Cathodic charging has been used successfully by Troiano (7) to demonstrate his diffusion-based theory of hydrogen embrittlement. It was suggested that this method might provide a better technique in the study of hydrogen embrittlement on submarine steels using the Lehigh restraint test. Therefore this experiment was designed to study the effect of cathodic charging on the crack sensitivity of the said steels. With an efficient method of charging it should be possible to introduce hydrogen alone in the test material with the least amount of contamination. Besides, this method permits the introduction of hydrogen directly into the base plate or

the electrode.

EXPERIMENTAL PROCEDURE

Materials and Specimen

The following steels were tested:

1. ASTM A201
2. ASTM A212
3. ASTM A203
4. ASTM A302
5. HY65
6. HY80

Steels 1 through 5 were one inch thick and tested in the as-rolled condition. Steel 6 was 1 1/2 in. thick and tested in the normalized (air cooled from 1650°F) condition. Chemical compositions are given in table 1. The microstructures of these steels are shown in figure 1.

Lehigh Restraint Test: The Lehigh restraint test developed by Stout, Tor, McGeady and Doan (5,6) was used. Figure 2 shows the test specimen. Single pass welding was used in the test. When a weld bead is laid in the groove of the specimen it is loaded by stresses developed on cooling due to thermal contractions. This simulates fabrication restraint such as that of two plates welded together on a ship structure. This test permits variation of the constraint on the weld bead by changing the depth of the fins shown in figure 2.

The test variables are classified by Stout (5,6) as "external factors" and "internal factors". The "external factors" are those that can be directly controlled such

as plate composition, thickness, temperature, groove geometry, electrode, its composition and diameter and heat input, etc. The "internal factors" are those over which there is only indirect control such as cooling rate, penetration, composition of the fused metal resulting from the dilution of the deposited metal. Those that are beyond experimental control are called "inherent factors" such as diffusivity, physical properties of the weld and allotropic transformations.

By adopting suitable procedures it is possible to hold some of the variables constant and vary only those whose effects are to be evaluated.

From figure 2 we can see that the maximum restraint possible occurs when no slots are cut into the plate and this condition is called the 8 in. restraint. Thus the variation in restraint is expressed by the width of the specimen between the slots in inches.

For a test with specific conditions the maximum restraint which gives an uncracked bead is known as the critical restraint. The usefulness of the test is in its capability of showing quantitatively the effects of a particular variable on the cracking sensitivity of a steel.

Welding Technique

Three commercial electrodes, aluminum deoxidized, triple deoxidized, and a low-alloy composition, were used. A pure iron electrode was used with ASTM A201 steel.

Table 2 contains the compositions of the electrodes.

The shielded inert gas metal arc process was used. The welding atmosphere was 99.95% pure argon, which was passed over anhydrous calcium sulphate to ensure ultra dry conditions. Wet argon saturated with water by bubbling through water bottles was used whenever it was desired to introduce hydrogen in the arc atmosphere. The standard welding conditions were 250 amperes arc current, 15"/min. arc travel, and a gas flow of 55 cu. ft. per min. All tests were made under these conditions except that A212 was also welded at a higher current of 300 amperes. The pure iron electrode welds were also made at a higher arc current of 300 amperes and the arc travel was 10 in. per minute.

Restraint tests were conducted under ultra dry conditions of plate, electrode, and welding gas. The following procedure was used to ensure minimum possible hydrogen in the weld.

1. Bake base plates at 700°F for 48 hrs.
2. Bake welding electrode at 180°F for 1 hr. prior to welding.
3. Use dry argon.
4. Degrease groove and dry before welding.

Electrolytic charging of the plate was used to test the effect of introducing hydrogen in the base plate. This test was done to parallel the ultra dry conditions.

The charged electrode condition was similar to the charged plate except that instead of the plate the electrode was cathodically charged.

Cathodic Charging

Specimens were hydrogenated by cathodically charging in electrolyte made of 4% sulphuric acid in water with As_2O_3 as an inhibitor with a current density of .02 ampere per square inch for 10 hours at room temperature. Welding was performed less than one hour after charging. The charged specimen surface was neutralized with NaOH solution, wire brushed, degreased with CCl_4 and dried before welding. Tensile tests and Charpy tests were conducted on charged and uncharged specimens to evaluate charging.

In order to see if the specimen gave out diffusible hydrogen after charging, the evolution test described by Beachum (3) was used. Four A212 steel specimens 5" x 1" x 1" were charged cathodically and two were immediately introduced into inverted graduated cylinders in liquid paraffin saturated with hydrogen. The other two were welded with 4 1/2" long beads using the same welding conditions as with the Lehigh restraint specimens, quenched in water for 30 seconds dried and then introduced in the graduated cylinders in less than two minutes after weld. A record of gas evolved was sought.

Crack Detection

Stout (5) has shown that when the weld cracks the separation is at least .005 inch. A system of transducers--figure 3--connected to a time versus displacement recorder was used to detect cracking time and crack separation. The recorder was calibrated and found sensitive to .0001 inch crack expansion.

The transducer in question essentially is an instrument that works exactly under the principle of an extensometer used in a tensile testing machine. The crack separation is detected by the core movement in the transducer and indicated by the chart recorder. The transducer is mounted on one side of the bead using a brass mount fitted into a hole driven into the plate and held by a wing nut. A similar mount on the opposite side carries an adjustment screw which permits the setting of the pointer of the chart recorder in the desired position. So long as there is no cracking the chart prints a straight line. A crack is indicated by a break in the line which shifts to a new position effected by the core movement in the transducer. The length of the line from the start to the break represents the time period and the amount of shift gives the expansion due to cracking.

The same test criteria as was used by Beachum (3) was used where it was considered that delayed cracks are those that take place after 15 minutes of testing. The

The purpose of this was to eliminate thermal effects. Fifteen minutes was chosen because within this time the temperatures in the plate equalize.

The cracks were examined for crack path, hardness of the weld area and martensite, etc. In order to do this a cross section of the bead was obtained from the restraint specimen as shown in figure 2 by broken lines.

RESULTS AND DISCUSSION

Evaluation of the Cathodic Charging Process

Notch tensile tests were performed on AISI 1020, 1040 and 4340 steels. Table 3 shows the data. There is a marked decrease in the ductility and notch tensile strength as a result of cathodic charging. The effect on the notch tensile strength is greater in the higher carbon and alloy steel.

Table 4 shows tensile test results on standard ASTM .252-inch diameter specimens in the unnotched condition. Steels HY80 and A203 indicate considerable loss in ductility as a result of charging. However, the yield and tensile strengths seem to increase.

Charpy data for the above two steels are presented in figures 4 and 5. There does not seem to be any marked effect. This is in agreement with the view that hydrogen embrittlement is not observed under impact conditions. This is true for the A203 steel. However, the HY80 steel seems to show a slight effect since the data points for the charged plates seem to be lower and more scattered than for the uncharged plates.

The preceding data clearly show that the cathodic charging process contemplated for use with Lehigh restraint test is productive of hydrogen embrittlement. The hydrogen evolution test was negative, since no evolution was observed. This is an indication that the

amounts of hydrogen introduced is limited.

Lehigh Restraint Tests

ASTM A212 Steel (Table 5)

Tests were performed on this steel with a 3-inch bead in a 3-inch groove. It may be noted at this point that the 3-inch bead offers greater restraint than a 5-inch bead at the 8-inch level.

At the maximum restraint of 8 inches on a 3-inch bead, it was found that cathodic charging had no effect on the cracking tendency of welds produced with the triple deoxidized wire. However, charging induced cracking in plates welded with the alloy electrode.

The crack lies entirely in the bead (figure 6). Martensite was seen in the center of the grains surrounded by pearlite at the grain boundaries in the heat affected zone. A hardness survey (table 11) for this specimen indicated that the bead is stronger than the heat affected zone.

ASTM A203 Steel (Table 6)

Tests were performed at the maximum restraint of 8 inches on a 3-inch bead. No cracking was observed in any of the tests. This was the least crack sensitive steel. A hardness survey indicated that the base plate has a hardness of Rockwell "C" 6-7 whereas the bead as well as the heat affected zone have a hardness of Rockwell "C" 38-39.

The combination of a strong weldment in relatively weak material is probably the reason for the behavior of the steel in this test. In other words, the restraint on the bead is relieved due to yielding in the base plate to levels lower than would be necessary to initiate cracking.

ASTM A302 Steel (Table 7)

This steel was the most crack sensitive in the "ultra dry" condition itself. The cracking level of restraint on a 5-inch bead was low for both the triple deoxidized and alloy electrode.

Only the alloy electrode showed effects of charging. The critical restraint fell from 3 inches to 2.5 inches on charging the plate.

The cracks (figure 7) for the major part lie in the heat affected zone. They are transcrystalline in nature. The crack path runs across grains which contain substantial amounts of martensite. In some cases as in test No. 44 (figure 7) the crack runs into the bead in the upper portion of the weld. This is probably due to the stress pattern developed in the weld vicinity. The cracks in this steel happened after significant delays up to 55 hours. The time delay increases as the restraint level is decreased. The microstructure of the steel showed heavy banding and inclusion stringers. The stringers may act as internal stress raisers to increase the crack sensitivity of this steel. The hardness survey in table 11 indicates that the

heat affected zone is stronger than either the bead or the base plate.

ASTM A201 Steel (Table 8)

This steel was used in order to investigate whether hydrogen embrittlement could be observed in the weldment of a low carbon steel using pure iron electrode. In other words, it was attempted to see if delayed cracking is possible in a weldment where the carbon level is so low that martensite may not be formed. Even at the maximum restraint cracking was not observed both in the ultra dry condition as well as charged plate condition.

The same observation was made when alloy electrode was used instead of the pure iron. The cracking was absent in spite of the fact that water vapor and hydrogen gas were introduced in the arc atmosphere.

This steel is highly ductile and has relatively low strength. This fits in with the observations made on the A203 steel which is also a relatively ductile steel. The results are consistent with the theory that strong martensite is essential for the delayed cracking of steel weldments.

HY65 Steel (Table 9)

Three electrodes were used for tests on this steel. Under the ultra dry condition cracking did not take place at the maximum restraint level.

Cracking was induced in the charged plate condition for aluminum deoxidized electrode and the alloy electrode. Charging electrodes did not result in cracking for the three electrodes.

The triple deoxidized electrode showed anomalous results, in that, the time delay decreased with the decreasing restraint. It was suspected that the copper coating on the wire may have caused this by trapping hydrogen, which was prevented from diffusing out through the copper coating in the baking operation. This was confirmed, when the welds were repeated after scraping the copper coating prior to baking the wire. This procedure eliminated cracking. The cracks (figure 8) lie in the bead and seem to start from the root notch. Hardness survey (table 11) indicates that bead and heat affected zone are equally strong, but stronger than the base plate. It was observed that the cracking time increases with the decreasing restraint. Small amounts of martensite were seen in the heat affected zone.

HY80 Steel (Table 10)

Effect of charging was well demonstrated by this steel. In the ultra dry condition the crack sensitivity increases with the following order of the electrodes--aluminum deoxidized alloy and triple deoxidized electrodes.

Effect of charging the plate was shown only in the case of triple deoxidized and alloy electrodes. Charging

the electrode was effective with all the three electrodes. As in the case of A302 steel, the cracks were (figures 9, 10 and 11) in the heat affected zone. The time delay for cracking increases with the decrease in the restraint. Hardness survey (table 11) indicated that the heat affected zone was stronger than the bead and the base plate. The cracks are transcrystalline. Significant amounts of martensite could be seen in the microstructure of the heat affected zone.

Discussion

It was found possible to induce delayed cracking by the introduction of hydrogen through cathodic charging. On comparison with the data produced by Interrante (8) in similar tests where hydrogen introduction was by adding water vapor and hydrogen gas to the arc atmosphere, it was found that the critical restraint in the case of ultra dry and cathodic charging is usually higher. This indicates that the hydrogen introduced by the charging process is much lower, and baking for ultra dry condition is effective. A comparative chart is presented in figure 12. It is not possible to make any positive conclusions with the limited data in regard to behavior for different base plate, electrode combinations. However, a careful study would indicate that the crack sensitivity increases with the order of the electrodes--aluminum deoxidized, triple deoxidized and alloy electrodes. Another trend that may be seen is that

the delayed cracking tendency increases on going to a higher strength steel. The reason is that the high strength steels easily form martensite and can develop higher internal stresses. Cathodic charging was ineffective in A201 steel. Some cracking was observed due to cathodic charging in steels A212 and A302. A considerable effect was exhibited by HY65 and HY80 steels which have a higher strength and contain alloy which increase the hardenability like chromium, molybdenum and vanadium. The hardness survey results show that generally the crack lies in that area which has the higher hardness. This observation is quite consistent in view of the fact that hydrogen embrittlement is a result of high stresses, hydrogen and strong martensite. The crack in the heat affected zone usually passes through the regions of coarse grains. Martensite is mostly observed in this area of coarse grains. The dependence of delayed cracking on hydrogen content and stresses is clearly demonstrated by the fact that the cracking time increases with decreasing restraint and that adding hydrogen by charging decreases the critical restraint.

The anomalous result observed with HY65 and triple deoxidized elcctrode fits well with the fact that this electrode has the highest hydrogen content (table 2).

CONCLUSIONS

1. Cathodic charging can be effectively used for studies involving hydrogen embrittlement. It is effective on the Lehigh restraint test. Pronounced results are obtained by charging the plate.
2. Hydrogen embrittlement is more pronounced in high strength steels.
3. Delayed cracking is dependent on the amount of hydrogen and internal stresses.
4. Martensite appears to be a requirement to cracking, in the heat effected zone.
5. The crack appears to originate in the harder constituent of the weld area.
6. It was not possible to induce delayed cracking for low carbon steel with pure iron electrode, in other words, under conditions where martensite is unlikely.
7. Copper coating on the electrode can be deliterious due to trapped hydrogen, which can enter the weld bead during welding and result in delayed failures.

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TABLE 1

CHEMICAL ANALYSIS OF THE BASE PLATE STEELS

	A212	A302	A201	A203	HY65	HY80*
C	.32	.24	.11	.15	.12	.23
Mn	.71	1.37	.69	.64	.48	.1/.4
Si	.24	.24	.23	.25	.20	.12/.38
P	.02	-	.017	.01	.013	.040
S	.019	-	.025	.026	.032	.045
Ni	.02	.28	-	3.64	2.16	2.68/3.62
Cr	.03	.20	-	.05	.06	1.29/1.91
Mo	.01	.47	-	.05	.39	.37/.63
Al	.005	-	-	.019	.058	-
V	-	-	-	.02	.11	-
Ti	-	-	-	.006	-	-
Cu	-	-	-	-	-	-

*Since data not available the standard specification is shown.

TABLE 2

COMPOSITIONS OF THE WELDING ELECTRODES

Electrode	Triple Deox.	Al Deox.	Alloy	Pure Fe
C	.05	.12	.05	.003
Mn	1.48	1.27	1.32	<.03
P	.015	.016	.009	.001
S	.014	.025	.012	.008
Si	.56	.47	.55	<.03
Ni	.09	.09	1.32	.04
Cr	.03	.06	.09	.02
Mo	.02	.04	.43	.01
V	-	-	.15	<.01
Al	.06	.052	-	-
Ti	.10	-	-	-
Zr	.04	-	-	-
N	.008	.009	.011	<.01
H	21×10^{-5}	13×10^{-5}	7×10^{-5}	.0008
O	.0257	.0135	.0104	.059
Cu	-	.17	-	<.01

TABLE 3

NOTCH TENSILE TEST DATA

Steel	1020	1040	4340
	Normalized		
% Reduction in Area			
Uncharged	39.01	24.20	6.91
Charged	21.59	9.59	1.1
N.T.S. (Psi)			
Uncharged	24,839	31,155	73,766
Charged	24,866	30,481	25,883
	Quenched and Tempered		
% Reduction in Area			
Uncharged	6.55	2.53	4.35
Charged	1.29	1.64	1.19
N.T.S. (Psi)			
Uncharged	57,248	82,597	83,085
Charged	40,054	23,383	6,520

ASTM Standard .505" specimen with Charpy "V" notch with a notch depth of .075".

Charging time - 2 hrs.

TABLE 4

TENSILE TEST DATA

Steel	HY80	A203
% Reduction in Area		
Uncharged	57.4	61.6
Charged	0	30.2
Yield Strength		
Uncharged	114,050	41,750
Charged	114,910	51,330
Tensile Strength		
Uncharged	130,960	65,380
Charged	132,510	75,460

Charging time - 10 hrs.

Rate of loading - .02"/min.

TABLE 5

ASTM A212 Steel			Delayed Cracking Data				
No.	Electrode	Condition	Groove	Bead	Restraint	Crack	Time
B23	Triple Deox.	Ultra dry	3"	3"	8"	No	-
V6		Charged plate	3"	3"	8"	No	-
V16		Charged electrode	3"	3"	8"	No	-
V82	Alloy	Ultra dry	3"	3"	8"	No	-
V7		Charged plate	3"	3"	8"	Yes	50 min.
V14		Charged electrode	3"	3"	8"	No	-

TABLE 6

ASTM A203 Steel		Delayed Cracking Data				
No.	Electrode Condition	Groove	Bead	Restraint	Crack	Time
V24	Al Deox. Ultra dry	5"	5"	8"	No	-
		3"	3"	8"	No.	-
V42	Charged plate	5"	5"	8"	No	-
V45		3"	3"	8"	No	-
V72	Charged electrode	5"	5"	8"	No	-
V67		3"	3"	8"	No	-
V26	Triple Deox. Ultra dry	5"	5"	8"	No	-
V40		3"	3"	8"	No	-
V43	Charged plate	5"	5"	8"	No	-
V47		3"	3"	8"	No	-
V74	Charged electrode	5"	5"	8"	No	-
V75		3"	3"	8"	No	-
V51	Alloy Ultra dry	5"	5"	8"	No	-
V54		3"	3"	8"	No	-
V59	Charged plate	5"	5"	8"	No	-
V60		3"	3"	8"	No	-
V69	Charged electrode	5"	5"	8"	No	-
V26		3"	3"	8"	No	-

TABLE 7

ASTM A302 Steel			Delayed Cracking Data				
No.	Electrode Condition		Groove	Bead	Restraint	Crack	Time
V23	Triple Deox.	Ultra dry	5"	5"	8"	Yes	1.5 hrs.
V27			5"	5"	6"	Yes	27 hrs.
V36			5"	5"	4"	Yes	34 hrs.
V41			5"	5"	3"	Yes	55 hrs.
V49			5"	5"	2.5"	No	-
V57		Charged plate	5"	5"	2.5"	No	-
V35	Alloy	Ultra dry	5"	5"	8"	Yes	15 hrs.
V38			5"	5"	6"	Yes	16 hrs.
V44			5"	5"	4"	Yes	24 hrs.
V50			5"	5"	3"	No	-
V56		Charged plate	5"	5"	3"	Yes	12 hrs.
V62			5"	5"	2.5"	No	-

TABLE 8

ASTM A201 Steel			Delayed Cracking Data				
No.	Electrode	Condition	Groove	Bead	Restraint	Crack	Time
V89	*Pure iron	Ultra dry	5"	5"	8"	No	-
V90			3"	3"	8"	No	-
V91		**Charged plate	5"	5"	8"	No	-
V92			3"	3"	8"	No	-
V108	Alloy	**Wet argon	5"	5"	8"	No	-
V111		**Charged plate	5"	5"	8"	No	-
-		**Wet argon & 5% H_2	3"	3"	8"	No	-

*Pure iron electrode was welded at 300 amperes at 10"/min. arc travel rate.

**(Wet argon) water vapor introduced in arc atmosphere.

TABLE 9

HY65 Steel No.	Electrode Condition	Groove	Bead	Restraint	Crack	Time
V86	Al Deox. Ultra dry	3"	3"	8"	No	-
V96	Charged plate	3"	3"	8"	Yes	30 min.
V99		3"	3"	6"	Yes	1 hr. 18 min.
V110		3"	3"	4"	No	-
V115	Charged electrode	3"	3"	8"	No	-
V93	Triple Deox. Ultra dry	(a) 3"	3"	8"	Yes	3 hrs.
V98		(a) 3"	3"	7"	Yes	2 hrs.
V116		(b) 3"	3"	8"	No	-
V117	Charged plate	(b) 3"	3"	8"	No	-
V118	Charged electrode	(b) 3"	3"	8"	No	-
V84	Alloy Ultra dry	3"	3"	8"	No	-
V94	Charged plate	3"	3"	8"	Yes	16 min.
V100		3"	3"	6"	Yes	1 hr.
V109		3"	3"	5"	No	-
V113	Charged electrode	3"	3"	8"	No	-

(a) Welded with the copper coating on the electrode.

(b) Copper coating removed before baking the electrode.

TABLE 10

HY80 Steel			Delayed Cracking Data				
No.	Electrode	Condition	Groove	Bead	Restraint	Crack	Time
V52	Al Deox.	Ultra dry	5"	5"	8"	No	-
V58			3"	3"	8"	No	-
V61		Charged plate	5"	5"	8"	No	-
V63			3"	3"	8"	No	-
V68		Charged electrode	5"	5"	8"	Yes	19 hrs.
V77			5"	5"	7"	No	-
V34	Triple Deox.	Ultra dry	5"	5"	8"	Yes	3 hrs.
V37			5"	5"	7"	No	-
V48		Charged plate	5"	5"	7"	Yes	45 min.
V53			5"	5"	6"	No	-
V73		Charged electrode	5"	5"	7"	Yes	1 hr.
V78			5"	5"	6"	Yes	7 hrs.
V81			5"	5"	5"	No	-
V25	Alloy	Ultra dry	5"	5"	8"	No	-
V39		Charged plate	5"	5"	8"	Yes	1 hr.
V46			5"	5"	7"	No	-
V66		Charged electrode	5"	5"	8"	Yes	7 hrs.
V71			5"	5"	7"	No	-

TABLE 11

HARDNESS SURVEY OF BEAD PROFILES

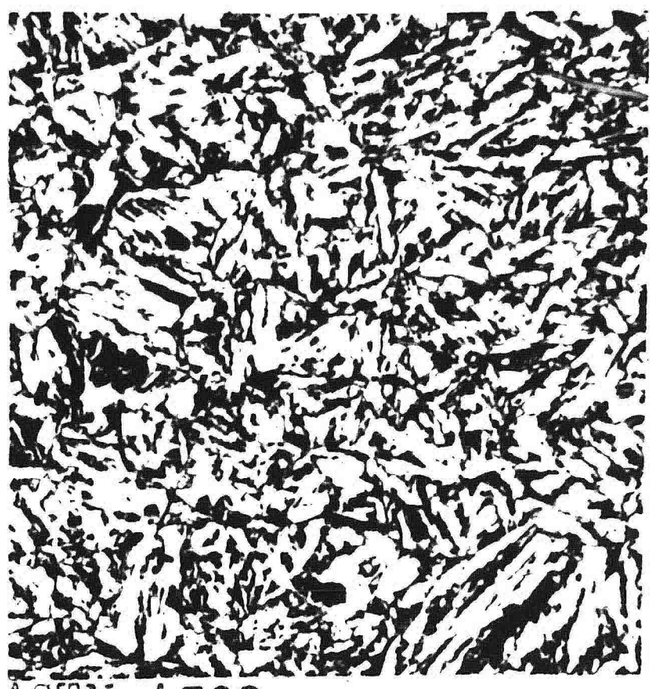
No.	Steel	Zone	Rockwell Hardness	Crack
V7	A212	Base plate	R"A" 50,50,52,52	-
		*HAZ	R"A" 61.5,64,62.5,59.5	-
		Bead	R"A" 67,67,67,66.5	Yes
V44	A302	Base plate	R"C" 22,23,23,20	-
		HAZ	R"C" 50,49,50,50	Origin
		Bead	R"C" 33,37,39,38	Extension
V99	HY65	Base plate	R"C" 14,16,14,17	-
		HAZ	R"C" 26,30,29,29	-
		Bead	R"C" 29,29,28,29	Yes
V100	HY65	Base plate	R"C" 19,16,16,20	-
		HAZ	R"C" 28,29,28,29	-
		Bead	R"C" 28,30,29,29	-
V39	HY80	Base plate	R"C" 32,32,34,32	-
		HAZ	R"C" 43,44,44,45	Origin
		Bead	R"C" 38,38,40,38	Extension
V68	HY80	Base plate	R"C" 34,32,32,33	-
		HAZ	R"C" 42,43,44,44	Origin
		Bead	R"C" 27,31,34,28	Extension

*HAZ heat affected zone

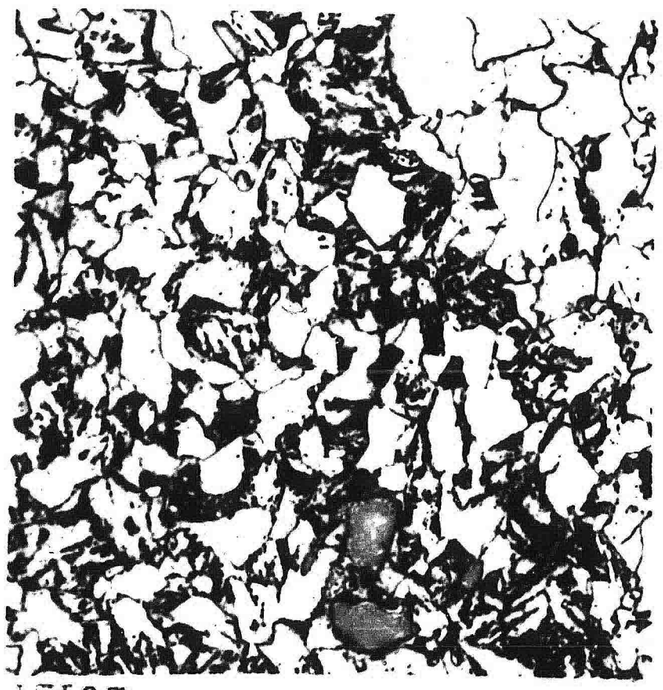
ASTM A201
Mag. 250X
Etchant: Nital

ASTM A212
Mag. 250X
Etchant: Nital

ASTM A203
Mag. 250X
Etchant: Nital



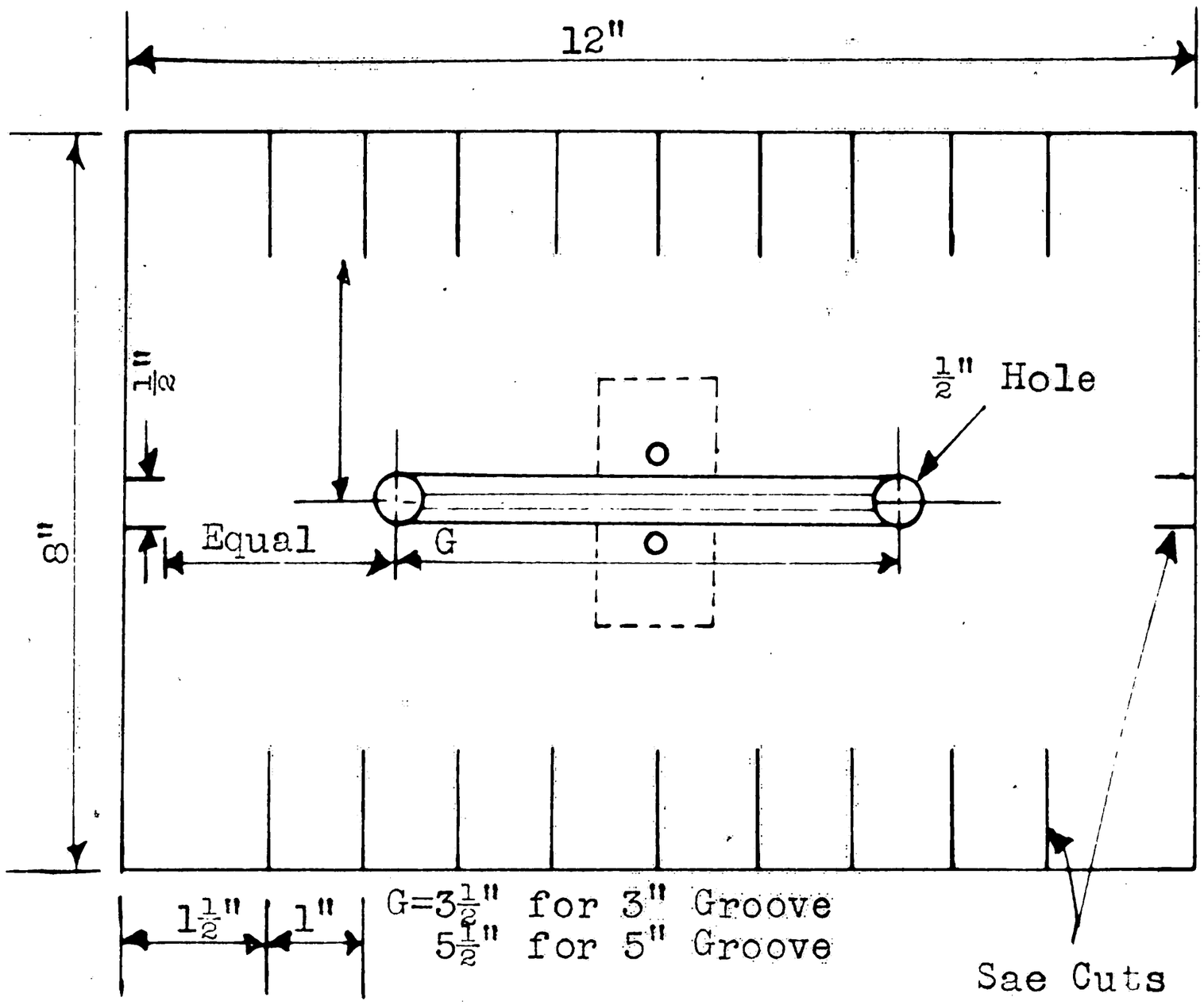
ASTM A302
Mag. 250X
Etchant: Nital



HY65
Mag. 250X
Etchant: Nital

HY80
Mag. 250X
Etchant: Nital

Figure 1. Microstructures of the Base Plate Steels.



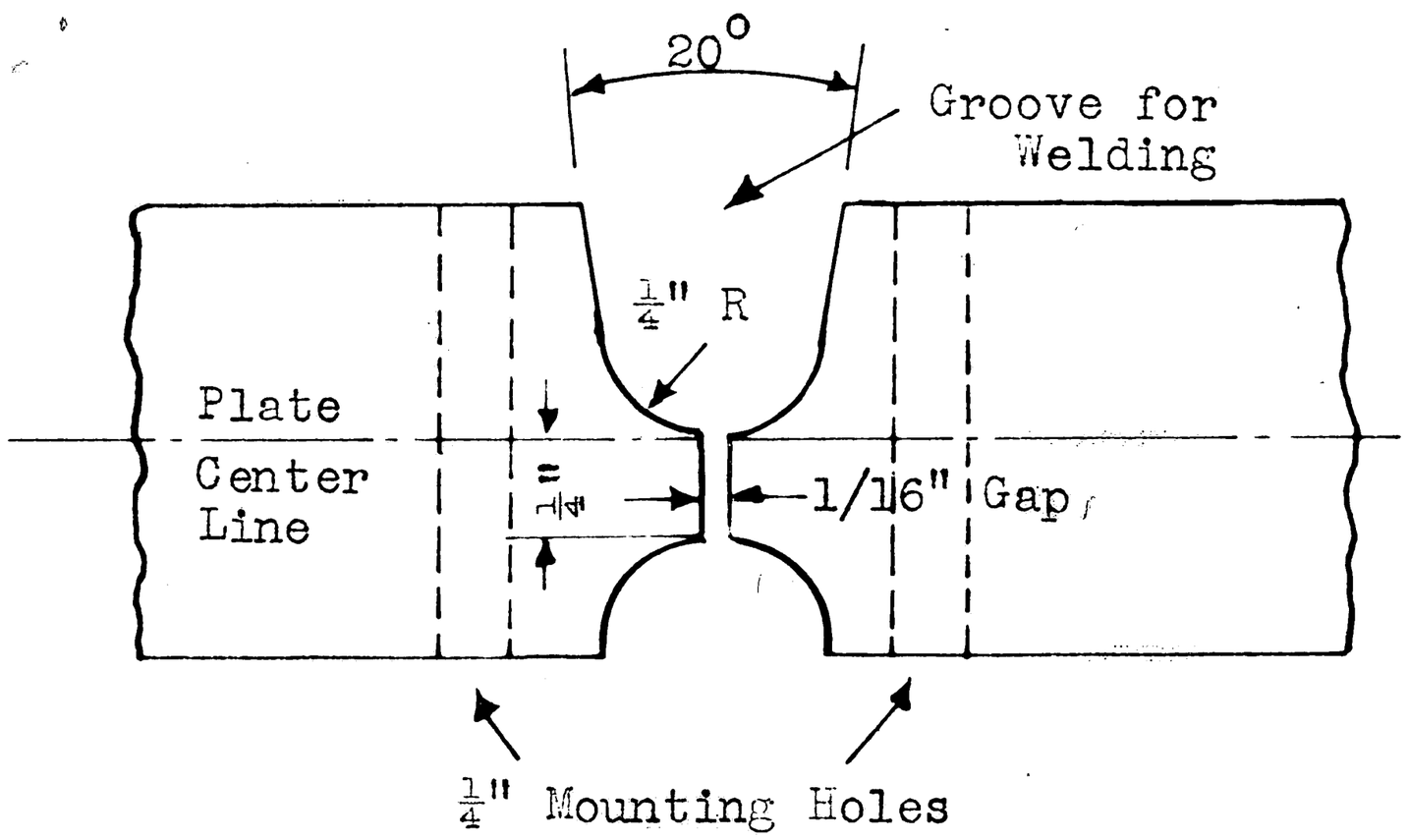


Figure 2. Lehigh Restraint Specimen

Figure 3. Transducer System for Crack Detection
(Approx. 3/4 Actual Size)
End View of Base Plate

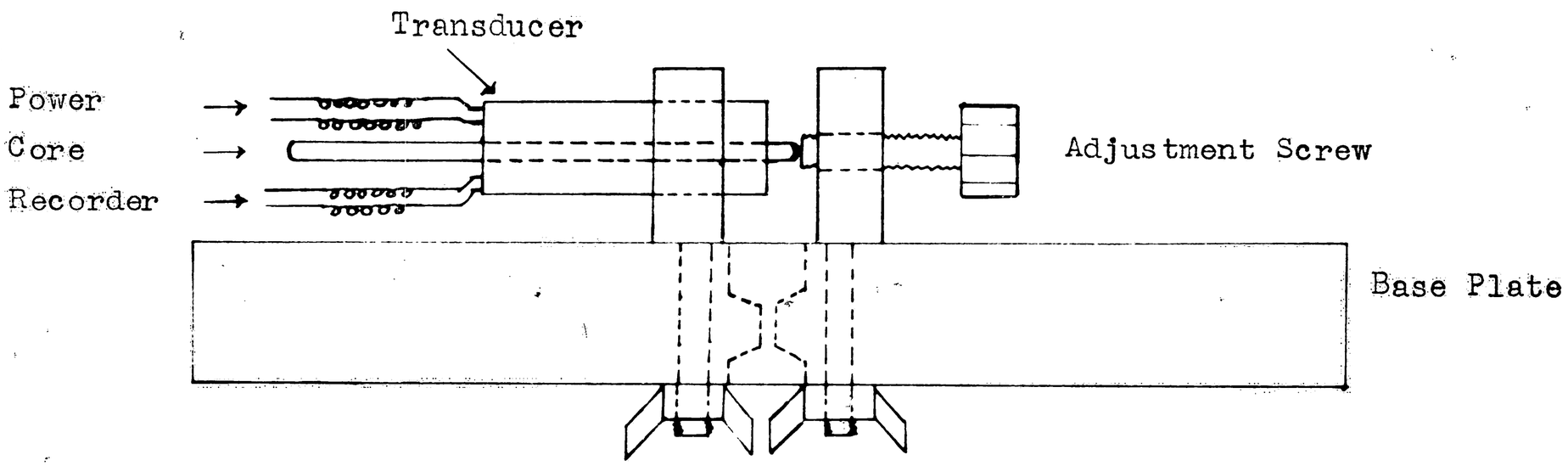


Figure 4. Energy Absorbed vs. Temperature
HY80 Steel
Normalized - 1650°F
"V" Notch Charpy

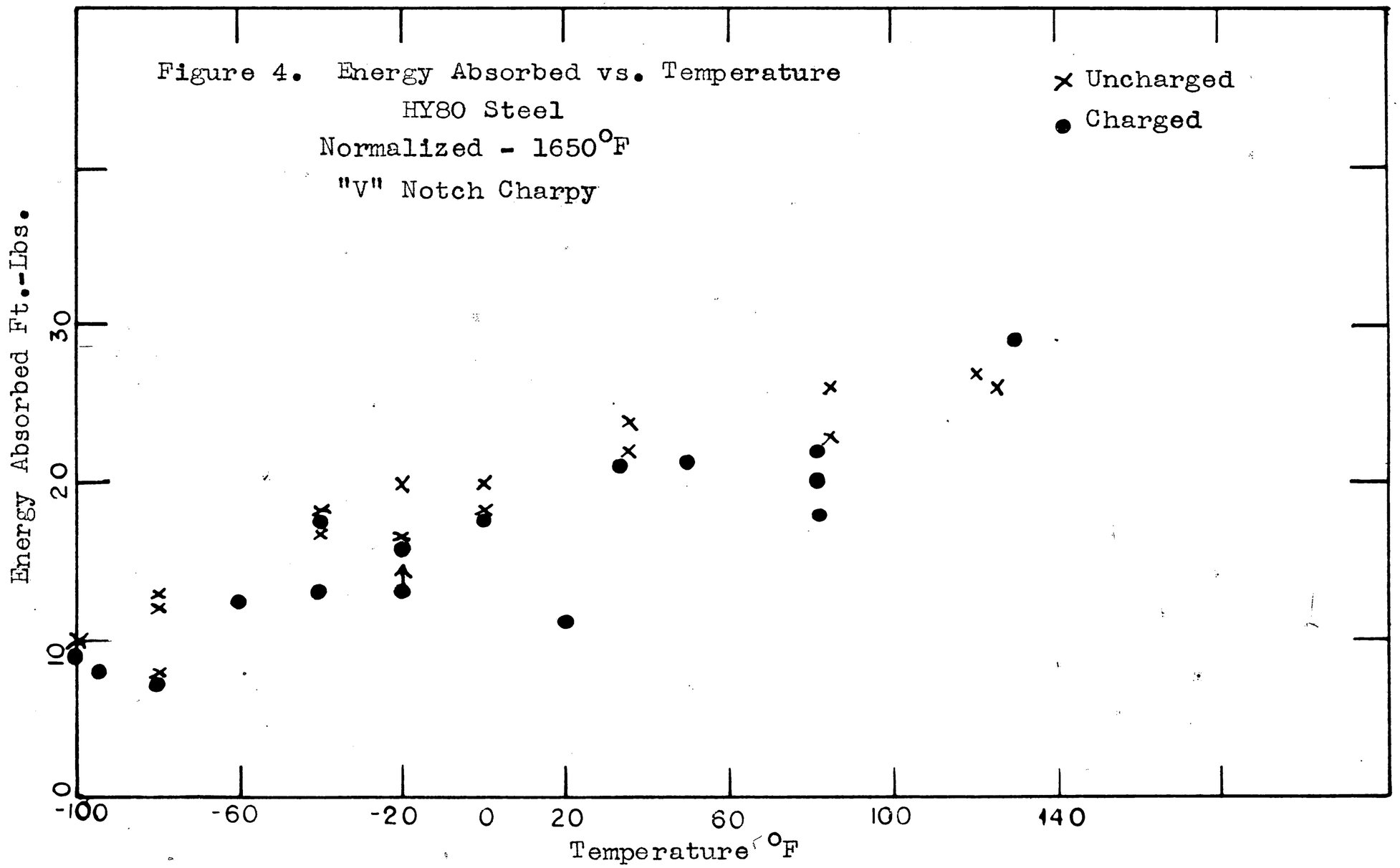
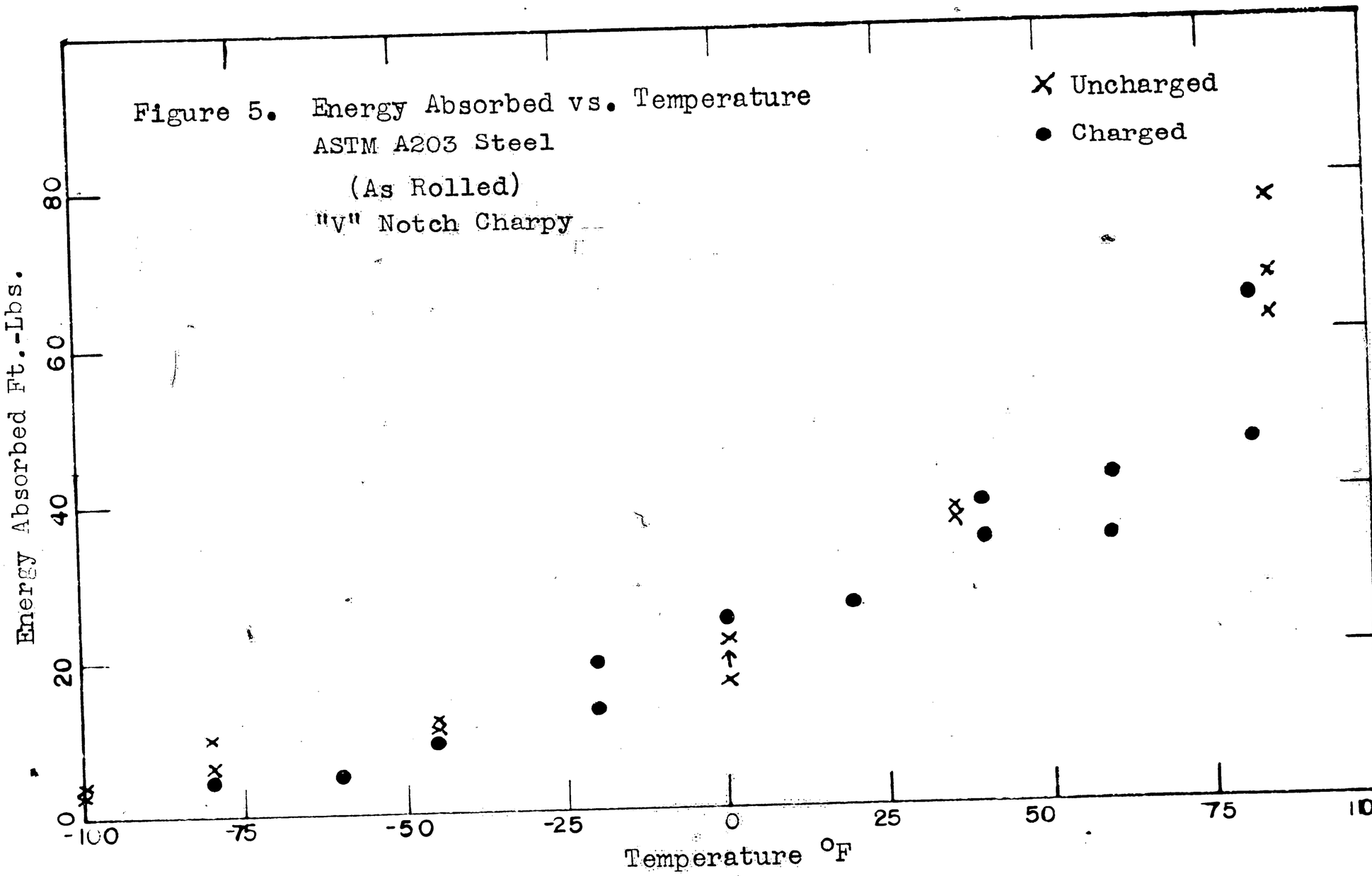
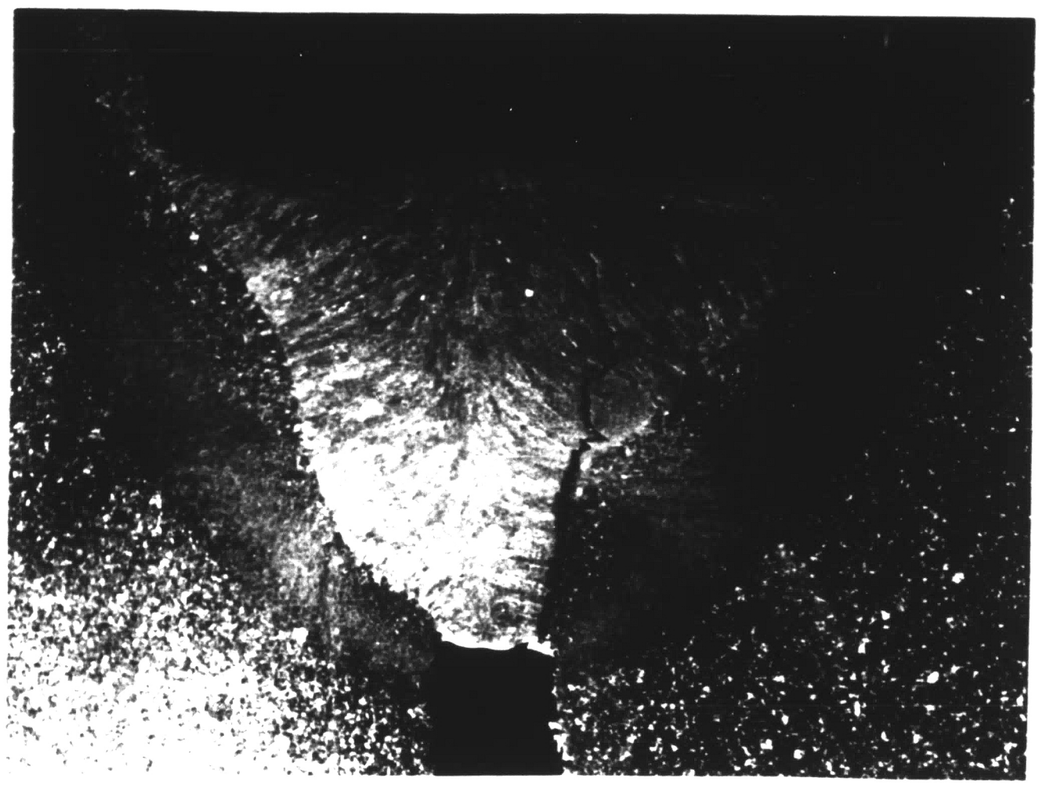


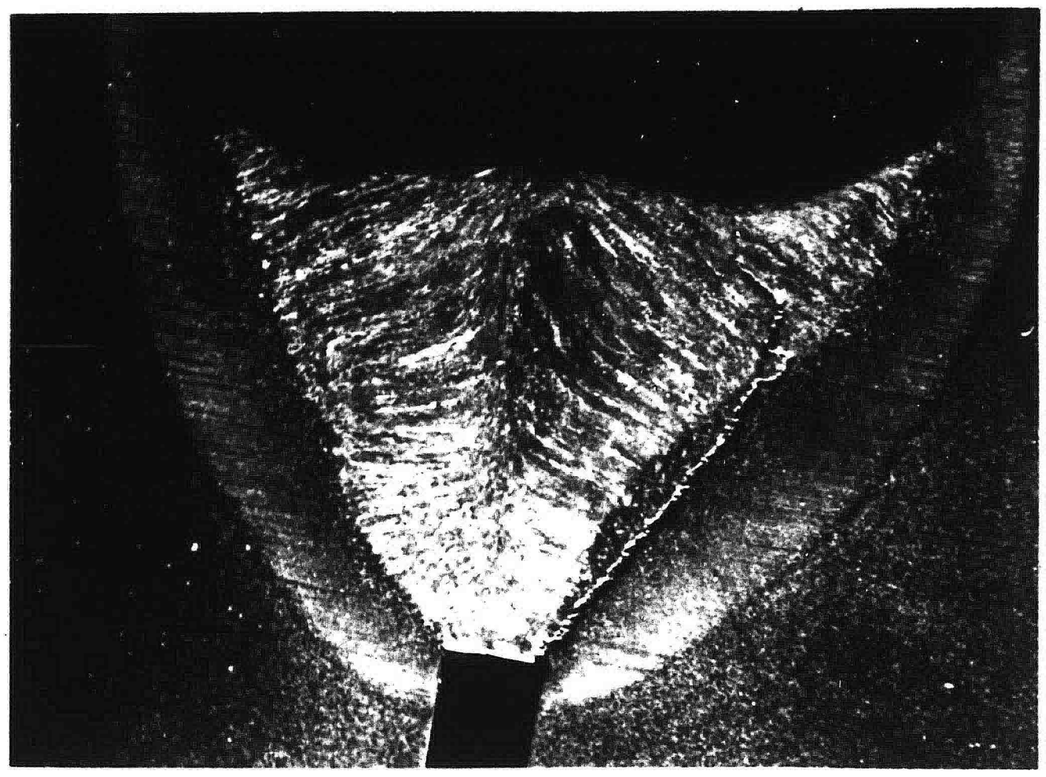
Figure 5. Energy Absorbed vs. Temperature
ASTM A203 Steel
(As Rolled)
"V" Notch Charpy



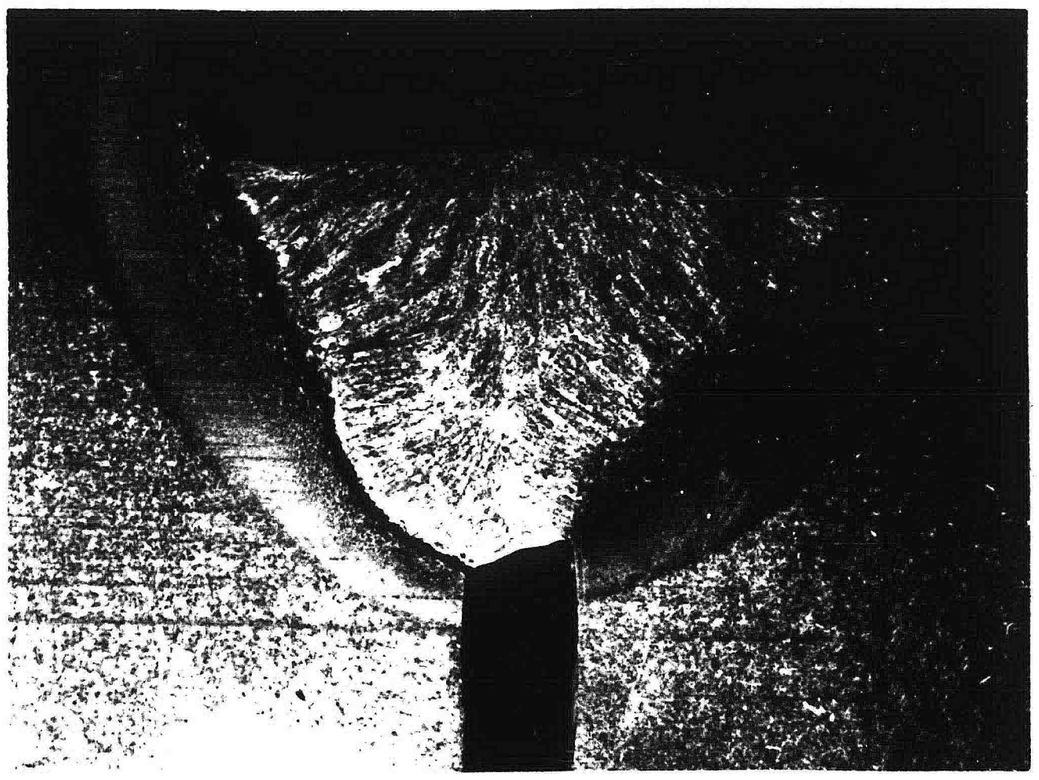


Mag.: 5.5X Test No. V7

Figure 6. ASTM A212 Steel:

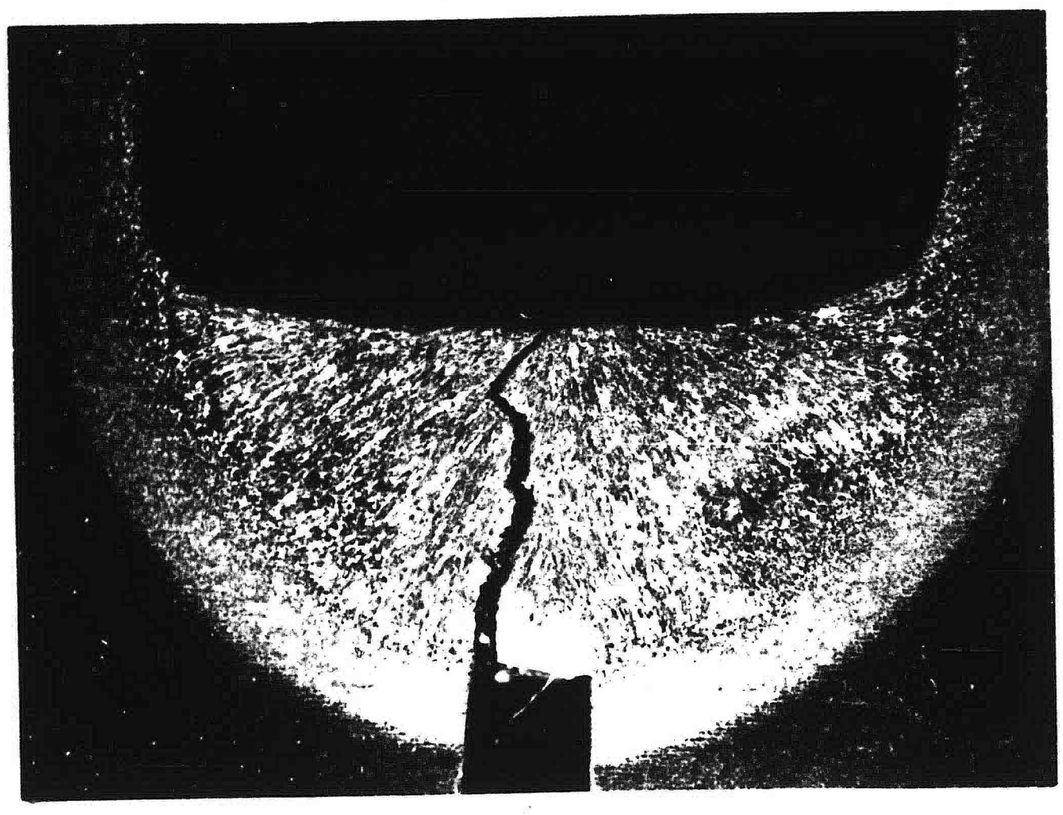


Mag.: 5.5X Test No. V44

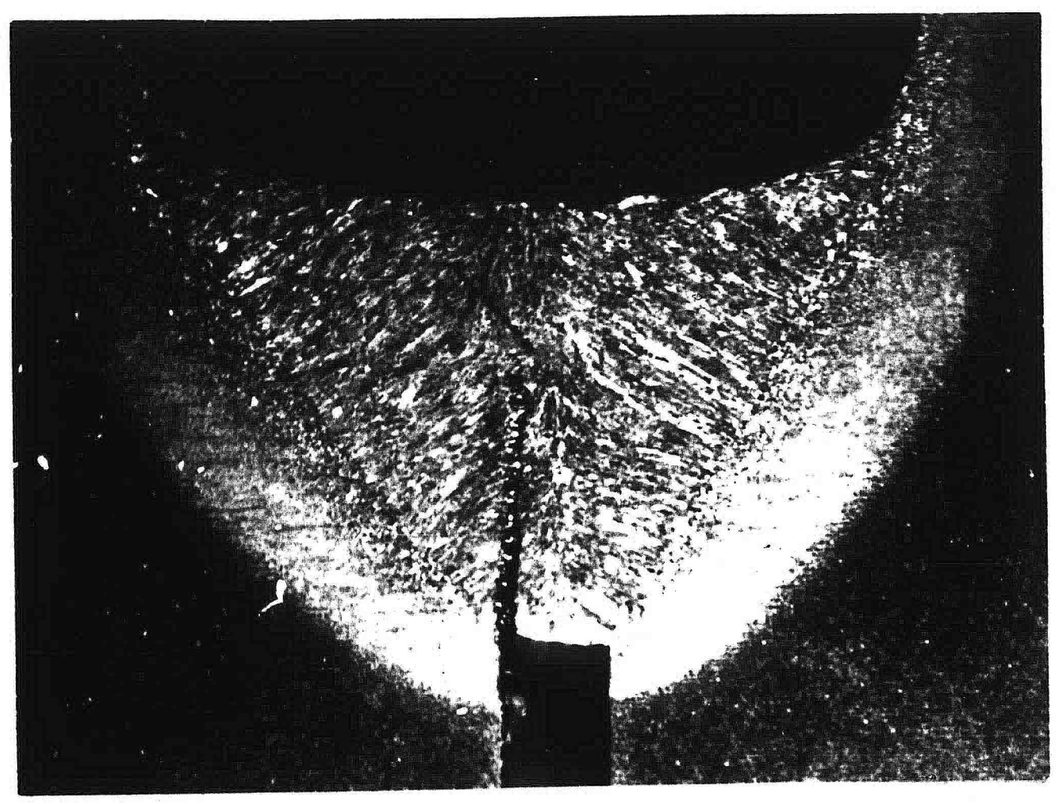


Mag.: 5.5X Test No. V56

Figure 7. ASTM A302 Steel.

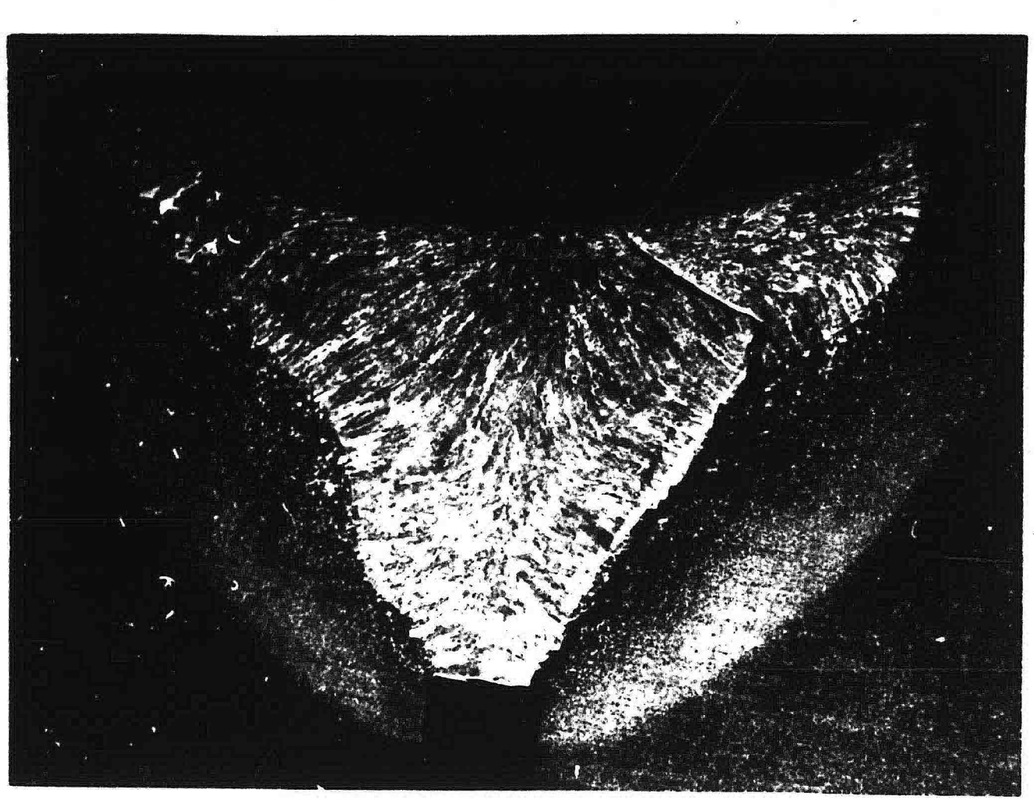


Mag.: 5.5X Test No. V99

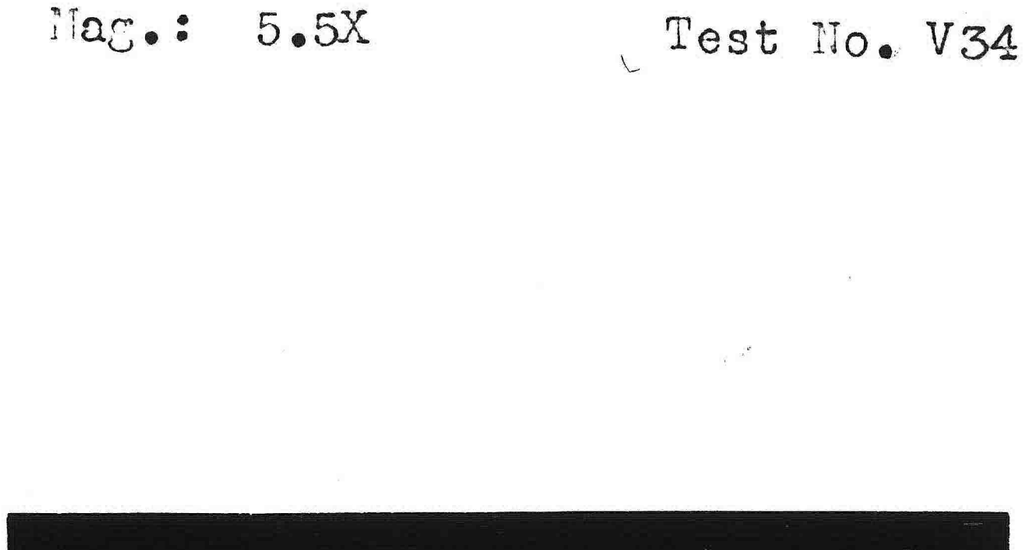


Mag.: 5.5X Test No. V100

Figure 8. HY65 Steel.

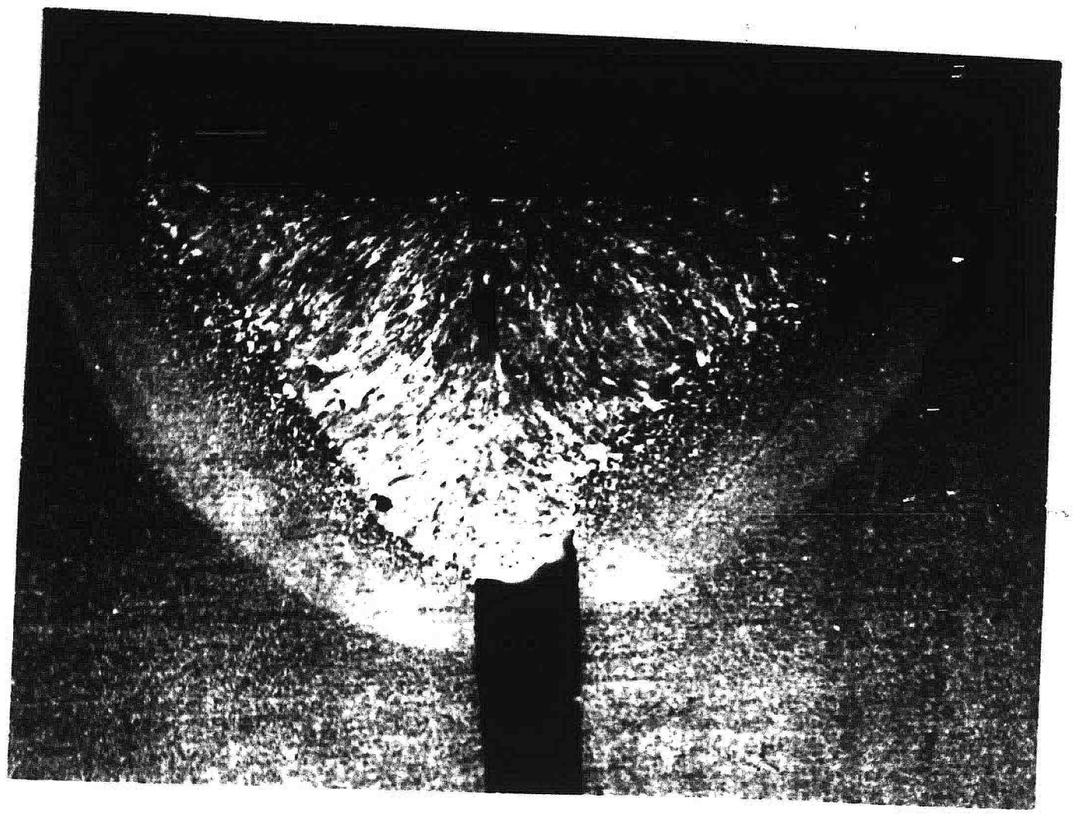


Mag.: 5.5X Test No. V34



Mag.: 5.5X Test No. V39

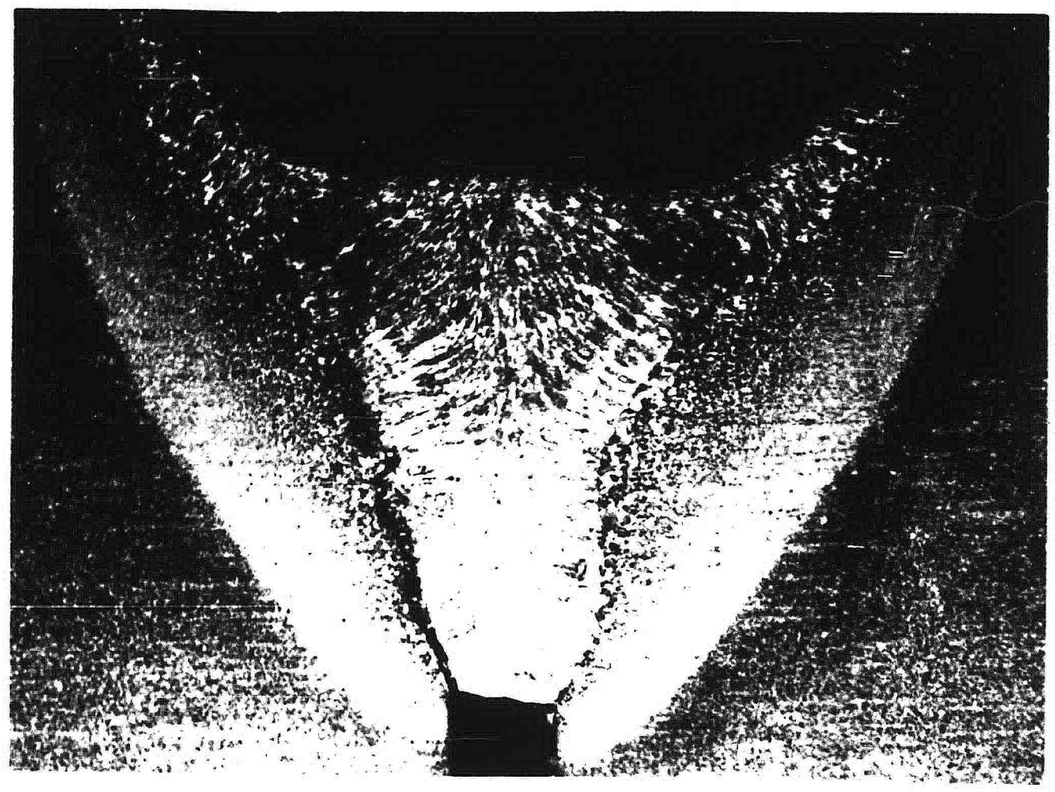
Figure 9. HY80 Steel.



Mag.: 5.5X Test No. V48

Mag.: 5.5X Test No. V66

Figure 10. HY80 Steel



Mag.: 5.5X Test No. 68

Figure 11. MO Steel.

Steel*	Elect.	Cond.	
A212 Steel	Triple Deox. Wire	dry	
		chgd. plate	
		chgd. electrode	50 min.
	Alloy Electr.	dry	
		chgd. plate	
		chgd. electrode	
			2 4 6 8 8 (3" groove)
A302 Steel	Triple Deox. Wire	dry	
		chgd. plate	none 34 hr. 27 hr. 1.5 hr.
			none
	Alloy Electr.	dry	
		chgd. plate	none 24 hr. 16 hr. 15 hr.
			none 12 hr.
			2 4 6 8
	Al	dry	
	Deox.	chgd. plate	none 78 min. 30 min.
	Wire	chgd. electrode	
HY65 Steel	Triple Deox. Wire	dry	
		chgd. plate	
		chgd. electrode	
	Alloy Electr.	dry	
		chgd. plate	none 1 hr. 16 min.
		chgd. electrode	
			2 4 6 8 8 (3" groove)
	Al	dry	
	Deox.	chgd. plate	
	Wire	chgd. electrode	none 19 hr.
1 1/2" HY80 Steel	Triple Deox. Wire	dry	
		chgd. plate	none 3 hr.
		chgd. electrode	none 45 min.
			none 7 hr. 1 hr.
	Alloy Electr.	dry	
		chgd. plate	none 11 hr.
		chgd. electrode	none 7 hr.
			2 4 6 8 8 (3" groove)

*Increasing Strength Level Downwards.

Restraint level in inches

Figure 12. Effect of Cathodic Charging on Crack Sensitivity.

VITA

The author was born on the 1st of February, 1938, in Mangalore, India, to V. S. and Shantha Kudva. He attended school in his home town and graduated from St. Aloysius College High School in 1953. In 1960, he graduated from the University of Bombay with a Bachelor of Science Degree in Chemistry. Following graduation he enrolled in the Department of Metallurgy at Lehigh University to pursue studies in metallurgy.